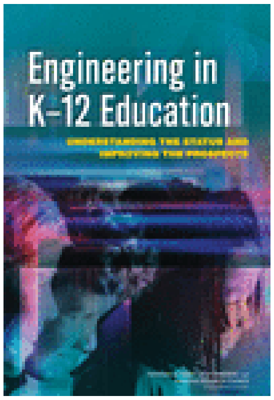

Engineering in K-12 Education: Understanding the Status and Improving the Prospects

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What Is Engineering?

To understand approaches to and the potential benefits of K–12 engineering education, one must first have an understanding of engineering itself. The word engineer is derived from the Medieval Latin verb *ingeniare,* meaning to design or devise (Flexner, 1987). The word *ingeniare* is, in turn, derived from the Latin word for engine, *ingenium*, meaning a clever invention. Thus, a short definition of engineering is the process of designing the human-made world. In contrast, science is derived from the Latin noun *scientia*, meaning knowledge, and is commonly described as the study of the natural world. Whereas scientists ask questions about the world around us—what is out there, how do things work, and what rules can be deduced to explain the patterns we see—engineers modify the world to satisfy people's needs and wants. Of course, in the real world, engineering and science can not be neatly separated. Scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers.

Usually, engineers do not literally construct artifacts. They develop plans and directions for how artifacts are to be constructed. Some artifacts are small—a hand calculator, for example, or a computer chip—and some are large—a bridge, for example, or an aircraft carrier. Engineers also design processes, ranging from the manufacturing processes used in the chemical and pharmaceutical industries to create chemicals and drugs to procedures for putting components together on an assembly line.

One useful way to think about engineering is as "design under constraint" (Wulf, 1998). One of the constraints is the laws of nature, or science. Engineers designing a solution to a particular problem must, for instance, take into account how physical objects behave while in motion. Other constraints include such things as time, money, available materials, ergonomics, environmental regulations, manufacturability, repairability, and so on.

This somewhat sterile description belies the inherently creative nature of engineering and its contribution to human welfare. As noted in a recent initiative to develop more effective ways of communicating to the public about engineering, engineers "make a world of difference. From new medical equipment and safer drinking water to faster microchips, engineers apply their knowledge to improve people's lives in concrete, meaningful ways" (NAE, 2008).

This introduction to engineering includes a brief history of engineering and its importance to society, a discussion of some defining features of engineering, and descriptions of relationships between engineering, science, and mathematics. Throughout this chapter, the reader should keep in mind that although engineers are crucial to shaping technology, they collaborate with professionals in many other fields, including scientists, craftspeople who build devices, business people who market and sell products, and a variety of technicians and technologists who are responsible for the operation, maintenance, and repair of devices.

A BRIEF HISTORY OF THE ENGINEERING PROFESSION

Engineers have been important in every stage of human history, because people have always designed and built tools and other devices. Today, however, the word engineer is used in a more specific sense to refer to a member of the engineering profession, which has evolved over the past 300 to 400 years.[1]

Origins

Some of the earliest examples of activities we might call engineering can be found in the context of major building projects, such as the construction of the system of aqueducts in and around Rome from the fourth century B.C. to the third century A.D. (Aicher, 1995; Evans, 1994). The aqueducts

[1]Much of the following short history of engineering is taken from a commissioned paper by Jonson Miller, Drexel University, a consultant to the project.

carried water from the outskirts of Rome to the city itself via a system of pipes, trenches, bridges, and tunnels.

A project of this sort today would be largely the responsibility of engineers, but the historical records of Rome do not mention anyone who played that particular role. Much of the construction and maintenance of the aqueducts was under the supervision of a *curator aquarum*, or water commissioner, but he (and it was almost certainly a man) seems to have been considered more of an administrator than anything else. The individuals who actually built and maintained the aqueducts were architects, surveyors, craftsmen of various sorts, and manual laborers (generally slaves), but not engineers. The concept of an engineer as we know it today did not yet exist.

Engineering as a Formal Discipline

Engineering first emerged as a formal discipline during the Renaissance, with the design of military fortifications. Historically, artisans had been in charge of both planning and constructing fortifications, but by the middle of the sixteenth century a group of non-artisan specialists had appeared who used geometry and mathematics to design fortifications in a more rational way and who generally let craftsmen take care of the actual construction. These specialized military architects were the first true engineers in the modern sense of the word.

Over time military engineers expanded their purview to include other military work, such as designing siege engines, as well as civilian projects, such as designing and planning transportation systems. Engineering was first formalized and professionalized in France, with the establishment of training programs that required formal examinations in mathematics, drawing, engineering theory, and other subjects (Langins, 2004). The first formal engineering schools were established in the mid-eighteenth century, also in France, and included the École des Ponts et Chaussées (School of Bridges and Roads) and the École Royale du Génie (Royal School of Engineering).

Later, when colonists in the nascent United States needed a corps of military engineers, they looked to France. During the Revolutionary War the Continental Congress established the Corps of Engineers to help design fortifications and artillery. After the war, the corps was given a home at West Point, New York, as director of the new U.S. Military Academy (Reynolds, 1991).

One purpose of the academy was to develop military engineers by providing training in mathematics, as well as in military and civil engineering. During the first half of the nineteenth century a number of individual states,

particularly southern states, started their own institutes, such as the Virginia Military Institute founded in 1839, that offered French-style engineering curricula. Most formal engineering training available in the United States up to the time of the Civil War was offered at these military academies.

Engineering as an Artisanal Craft

At the same time as a formal approach to engineering was being pursued in France, the United States and other countries adopted a second, more practical approach. The trend began in Great Britain with the advent of industrialization, when the country's artisans, who had a tradition of apprenticeships and on-the-job training, spearheaded the early design and development of the machinery and machine shops of the industrial age. The British transportation infrastructure was also developed by independent engineers who got their training through apprenticeships.

The apprenticeship tradition was transported to the 13 British colonies that would eventually become the United States, and the engineers who designed the machine shops and mechanized textile mills in the early days of this country had generally been trained in informal settings like those of typical British artisans and engineers (Calhoun, 1960; Reynolds, 1991). Similarly, many of the engineers who worked on road, bridge, and canal projects in the United States in the late 1700s and early 1800s were trained in this tradition—indeed, quite a few of them had learned their trades in Great Britain before coming to this country.

And so throughout much of the nineteenth century, engineers in the United States and elsewhere received their training in one of two very different ways—either a formal, theoretically oriented way that emphasized mathematics, science, and engineering theory, or a practical, hands-on way that favored on-the-job training.

The Rise of Professional Engineers

After the Civil War, engineering programs in the United States increasingly emphasized formal training, although on-the-job training remained important for a variety of engineering disciplines—particularly mechanical engineering—until the middle of the twentieth century. At the same time, in the years following the Civil War a number of engineering professional societies appeared: the American Society of Civil Engineers (ASCE) in 1865, the American Society of Mechanical Engineers in 1880, the American

Institute of Electrical Engineers in 1884, and so forth. These societies had a strong influence on how the various fields of engineering were developed. They influenced education and training programs for engineers, and they developed standards for industry as well as ethical codes for their members (Reynolds, 1991). Professional societies also helped define new fields of engineering, as when mining engineers split from the ASCE in 1871 to form the American Institute of Mining Engineers and when industrial chemists broke away from the American Chemical Society in 1908 to form the American Institute of Chemical Engineering.

The professionalization of engineering continued through much of the twentieth century. One of the most important trends over the past 50 years has been the increasing emphasis on mathematics and science in the education of engineers. When the Soviet Union launched the Sputnik satellite in 1957, the U.S. response included a national effort to increase the number of scientists and engineers coming through the educational pipeline and to emphasize the teaching of science and mathematics. As a result, engineering education began to put much more emphasis on theory and mathematics (Lucena, 2005).

Over the past quarter century, as the national focus has shifted from the perceived Soviet military threat to concerns about globalization and U.S. competitiveness in the world economy, the emphasis in engineering education has shifted again. Today, engineering schools no longer focus exclusively on science, mathematics, and engineering theory. They also emphasize flexibility and being able to respond quickly to emerging challenges (e.g., NAE, 2004). Expectations for engineering students are now likely to include the ability to work well in teams, to communicate ideas effectively, and to understand other cultures and the effects of technology on societies and individuals. In short, as technology has evolved from a collection of mostly isolated devices and structures to a tightly interconnected global system, engineers—as the designers of this technological world—have also evolved. Today, they must be competent in far more than the traditional science- and math-oriented subjects.

Engineering, Industrial Arts, and Technology Education

The advent of formal engineering education with its emphasis on theoretical mathematics and science was accompanied by a growing recognition that aspiring engineers also needed manual skills. As early as 1870, Calvin M. Woodward, dean of the engineering department at Washington Univer-

sity, instituted shop training for his engineering students after he found that they were unable to produce satisfactory wooden models to demonstrate mechanical principles. John D. Runkle, president of the Massachusetts Institute of Technology, introduced a similar program after seeing demonstrations of Russian manual arts training at the 1876 Centennial Exposition in Philadelphia. Both men believed that shop skills were essential for engineers (Sanders, 2008).

In the 1880s, under the leadership of Woodward and Runkle, Washington University and MIT established schools for intermediate and secondary students that provided a combined program of liberal arts and manual training. Other schools, however, emphasized training in specific trades to provide skilled workers for specific industries. Both types of schools grew quickly.

By the early twentieth century, there had been a conceptual shift from "manual training" to "industrial arts." Contrary to what many people assume, industrial arts represented a shift away from vocational training toward general education for all (Herschbach, 2009). Students studied how industry created value from raw materials in the context of the developing industrial society in America. The curriculum required the ability to use industrial tools, equipment, and materials in a laboratory setting, but the "shop experience" was a means to an end, not an end in itself.

By the mid-twentieth century, industrial arts had become a standard component in the public school curriculum. However, it continued to be confused with vocational education, which was also on the rise during this period. By the end of the century, the teaching of industrial arts had expanded to include an understanding of technology in general. In 1985 the Industrial Arts Association of America changed its name to the International Technology Education Association (ITEA).[2]

Since the name change and, especially, since publication of *Standards for Technological Literacy: Content for the Study of Technology* (2000), technology education teachers have increasingly sought to teach engineering concepts and skills to students (Lewis, 2004). But this shift has not been universal, and technology education is still best thought of as a continuum of practice spanning traditional industrial arts ("shop") classes, career-focused indus-

[2]The shift is evident in a 2009 ballot measure to change the name of the International Technology Education Association (ITEA) to include the word engineering. A full 65 percent of voting members favored the name change (K. Starkweather, ITEA, personal communication, June 16, 2009). However, the association's bylaws require a 66 percent majority, so the measure did not pass.

trial technology, and technology education programs that include differing degrees of engineering content.

The varied implementation of technology education makes it difficult to clearly distinguish it from "engineering education" at the K–12 level. The distinctions are most apparent between the industrial arts model of technology education, with its emphasis on tool skills and fabrication of technological artifacts, and engineering education that focuses on the engineering design process as an approach to problem solving. Some analysts (McAlister, 2007) have pointed out that pre-service education for most technology teachers includes relatively few mathematics and science courses. Because engineering design, particularly modeling and analysis, relies on mathematics and science concepts, another emerging distinction between educators in technology and those in engineering may be their degree of preparation in science and mathematics.[3]

More broadly, there are indicators of growing interest in understanding and improving the connections between engineering and technology education. For example, the ITEA Council on Technology Teacher Education devoted an entire volume to the topic (CTTE, 2008); from 2004 to 2009, the National Science Foundation funded the nine-university National Center for Engineering and Technology Education (*www.ncete.org*), in part to grow these connections; and in 2004, the American Society for Engineering Education established a Division on K–12 and Pre-College Engineering, and some members of the division are from technology education.

The Demographics of Engineering Today

In 2006, the most recent year for which data are available, the United States had an engineering workforce of about 1.5 million people[4] (BLS, 2008a). About 37 percent of engineering jobs were in manufacturing industries, and 28 percent were in the professional, scientific, and technical services sector, primarily architectural, engineering, and related services. Many engineers also worked in the construction, telecommunications, and wholesale trades. In addition, federal, state, and local governments employed about 12 percent of engineers.

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[3]The importance of mathematics and science to engineering design is discussed at length in Chapter 4.

[4]This number does not include roughly 27,000 engineering teaching personnel who are employed by engineering schools (ASEE, 2007a, p. 28).

Although this chapter is focused on the history of engineering, it is important to recognize another significant component of the technology workforce, engineering technicians and technologists. Formal engineering technology programs, which were developed in the mid-twentieth century, provide students with a distinctly hands-on, practical education, in contrast to engineering programs, which focus more on theory and design (Grinter, 1984). Today, there are both two- and four-year engineering technology programs in the United States. Graduates of the former are often called engineering technicians; graduates of the latter are called engineering technologists. Engineering technologists typically implement designs created by engineers. They may be involved in making incremental design changes, building and testing products and processes, managing the installation of complex equipment, and developing maintenance procedures. Engineering technicians are primarily operators of technology, but they also have installation and maintenance skills beyond the capabilities of skilled tradesmen. In practice, there may be considerable overlap between engineering technologists and engineering technicians.

In 2006, 511,000 engineering technicians were working in the United States, a third of them electrical and electronics technicians (BLS, 2008b). The U.S. government does not collect employment data on engineering technologists in a separate job classification. However, the Engineering Workforce Commission estimates that there were about 10,000 bachelor's degrees in engineering technology awarded in 2007 (ASEE, 2007b).

Women and minorities are greatly underrepresented in engineering schools (both as students and faculty) and engineering jobs in the United States relative to their proportions in the population at large (Table 2-1). Although their participation has been increasing over the past two decades, the rate of increase has slowed—and for women the upward trend has recently reversed. This situation has many people in the engineering community worried about the future supply of engineers, especially as the U.S. population becomes increasingly diverse.

Some have expressed a concern that other countries—particularly China and India—have been outpacing the United States in the production of engineers. Although it is difficult to make comparisons because of differences in the methods of collecting data and differences in how engineers are defined, the trends are clear. The number of engineering bachelor's degrees awarded in the United States has increased gradually over the past seven years to slightly more than 74,000 in the 2005–2006 school year (ASEE, 2007a). This is a jump of about 20 percent since 1999. In China, by contrast, the number

TABLE 2-1 Selected Data for Women, African Americans, Hispanics, and Native Americans in Engineering

Women
- Proportion of U.S. population, 2005 (est.): 50.7 percent
- Proportion of students enrolled in degree-granting institutions, 2004: 57.4 percent
- Proportion of bachelor's degrees in engineering, 2004: 20.5 percent
- Proportion of tenured/tenure-track appointments on U.S. engineering faculties, 2005: 10.6 percent
- Proportion employed as engineers, 2003: 11 percent

African Americans
- Proportion of U.S. population, 2004: 12.8 percent
- Proportion enrolled in degree-granting institutions, 2004: 12.5 percent
- Proportion of bachelor's degrees in engineering earned, 2004: 5.3 percent
- Proportion of tenured/tenure-track appointments on U.S. engineering faculties, 2005: 2.3 percent
- Proportion employed as engineers, 2003: 3.1 percent

Hispanics
- Proportion of U.S. population, 2004: 14.1 percent
- Proportion enrolled in degree-granting institutions, 2004: 10.5 percent
- Proportion of bachelor's degrees in engineering, 2004: 7.4 percent
- Proportion of tenured/tenure-track professors on U.S. engineering faculties, 2005: 3.2 percent
- Proportion employed as engineers, 2003: 4.9 percent

Native Americans
- Proportion of U.S. population, 2004: 1 percent
- Proportion enrolled in degree-granting institutions, 2004: 1 percent
- Proportion of bachelor's degrees in engineering, 2004: 0.6 percent
- Proportion of tenured/tenure-track professors on U.S. engineering faculties, 2005: 0.2 percent
- Proportion employed as engineers, 2003: 0.3 percent

SOURCES: NSF, 2005a,b, 2006a,b; U.S. Census Bureau, 2002, 2005; U.S. DOEd 2006a,b.

of students graduating with four-year degrees in engineering, computer science, and information technology more than doubled between 2000 and 2004 (Wadhwa et al., 2007). A similar doubling occurred in India.

The committee did try to ascertain the level of pre-college engineering education in India and China. The various individuals we spoke with, including high-level education and industry officials in both countries, indicated there were no such efforts. We were told that Indian and Chinese students'

first exposure to engineering ideas typically occurs in college. However, we could find no reliable evidence to confirm this.[5]

THE ROLE OF ENGINEERING IN MODERN SOCIETY

Over the past 400 years the role of engineers has expanded and diversified from a singular focus on military fortifications and engines to include products that affect almost every aspect of society and people's daily lives. Many of these are well known—engineers design both computers and the software that runs on them, both automobiles and the roads and bridges they travel on, and power plants and the transmission systems that carry power to the people who need it. In other respects, the accomplishments of engineers are not as widely recognized. For example, every piece of medical equipment, from the simplest thermometer to the most complex MRI device, was designed by an engineer, as were machines that are used to manufacture other machines and the equipment scientists rely on for work that often leads to scientific discoveries.

One way to get a sense of the importance of engineering in modern society is to examine the list of 14 grand challenges for engineering produced by the National Academy of Engineering (NAE) in 2008 (Box 2-1). These challenges are major issues confronting society in the twenty-first century, and engineering will be crucial to addressing all of them.

For instance, sustainability is a major theme linking five of the grand challenges. As societies search for ways to maintain themselves in a sustainable way relative to the environment, engineers will have to find ways to provide clean water and economical solar power and energy from fusion and develop ways to remove carbon dioxide from the atmosphere, such as storing it in the Earth's crust. Engineers, working with doctors and medical researchers, can improve human health by developing better ways of storing, analyzing, and communicating health information and by designing more effective drugs. To avoid the misuse of powerful technologies, engineers will find ways to keep terrorists from obtaining and using nuclear materials and technologies and to secure cyberspace. Finally, engineers in the coming century will be crucial to improving human capacities by, for example, advancing personalized learning and engineering the tools that will enable scientific discovery.

[5]For a brief review of pre-college engineering efforts in countries other than India and China, see the annex to Chapter 4.

BOX 2-1
Grand Challenges for Engineering

On February 15, 2008, the National Academy of Engineering announced its list of 14 “grand challenges for engineering,” examples of the types of challenges confronting societies in the twenty-first century. The solutions to these challenges will all have large engineering components. Although engineers cannot solve these challenges alone, neither can the challenges be solved without engineers.

The fourteen grand challenges are:

- Making solar power economical;
- Providing energy from fusion;
- Developing carbon-sequestration methods;
- Managing the nitrogen cycle;
- Providing access to clean water;
- Restoring and improving urban infrastructure;
- Advancing health informatics;
- Engineering better medicines;
- Reverse-engineering the brain;
- Preventing nuclear terror;
- Securing cyberspace;
- Enhancing virtual reality;
- Advancing personalized learning; and
- Engineering the tools of scientific discovery.

SOURCE: NAE, 2008.

DESIGN AS A PROBLEM-SOLVING PROCESS

Science, mathematics, and engineering all have domains of knowledge, process skills, and ways of looking at the world. Perhaps the most important for engineering is design, the basic engineering approach to solving problems. Using the design process, engineers can integrate various skills and types of thinking—analytical and synthetic thinking; detailed understanding and holistic understanding; planning and building; and implicit, procedural knowledge and explicit, declarative knowledge.

What Is Engineering Design?

Design is a deceptively common word that is used to describe what graphic artists do, what fashion designers do, what landscape architects do, and what flower arrangers do. But in the context of engineering, the word has a specific meaning. Design is the approach engineers use to solve engineering problems—generally, to determine the best way to make a device or process that serves a particular purpose. When electronic engineers design an integrated circuit chip, when transportation engineers design a subway system, when chemical engineers design a chemical processing plant, and when biomedical engineers design an artificial organ, they all use variants of the same basic problem-solving strategy—engineering design.

According to *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000), engineering design has a number of characteristic attributes. First, it is purposeful; a designer begins with an explicit goal that is clearly understood; thus design can be pictured as a journey with a particular destination, rather than a sightseeing trip. Second, designs are shaped by *specifications* and *constraints*. Specifications spell out what the design is intended to accomplish. Constraints are limitations the designer must contend with, such as costs, size requirements, or the physical limitations of the materials used. In addition, the design process is systematic and iterative. Engineering design is also a highly social and collaborative enterprise. Engineers engaged in design activities often work in teams, and communication with clients and others who have a stake in the project is crucial.

Over time, engineers have developed a variety of rules and principles governing the development of a design. Although the rules are not absolute, engineers understand that these principles are based on many years of accumulated experience and that without such rules engineers would be very much like tinkerers or amateur inventors.

Design is not a linear, step-by-step process. It is generally iterative; thus each new version of the design is tested and then modified based on what has been learned up to that point. Finally, there is never just one "correct" solution to a design challenge. Instead, there are a number of possible solutions, and choosing among them inevitably involves personal as well as technical considerations (ITEA, 2000, pp. 91–92).

Although there is no formula for engineering design that specifies step 1, step 2, and so on, there are a number of characteristic steps in a design process. One step, for example, is identifying the problem. As noted above, an explicit goal for a design is what distinguishes it from tinkering. A second step is generating ideas for how to solve the problem. Engineers often use

research or brainstorming sessions to come up with a range of design alternatives for further development. Another step is the evaluation of potential solutions by building and testing models or prototypes, which provides valuable data that cannot be obtained in any other way. With data in hand, the engineer can evaluate how well the various solutions meet the specifications and constraints of the design, including considering the trade-offs needed to balance competing or conflicting constraints. Engineers call this process *optimization*.

These steps are repeated as necessary. For example, an engineer may go all the way back to step 1, identifying the problem, if the research and prototypes turn up something unexpected. Usually, however, the results of various tests lead to a round of improvements—complete with brainstorming ideas, testing new prototypes, and so on—and yet another round of improvements, until enough iterations have been performed that the engineer is satisfied with the result. Once the finished product has been tested and approved, it can be produced and marketed (ITEA, 2000, p. 99).

How Design Compares with the Scientific Method

Engineering design is often compared with scientific inquiry, the core problem-solving approach used in science, and, indeed, the two approaches have a number of similar features. But they also differ in significant ways. By identifying the convergences and divergences, one can get a better idea of how the two approaches might fit together in a school curriculum (Lewis, 2006).

The most obvious similarity, or convergence, is that both design and scientific inquiry are reasoning processes used to solve problems, "navigational devices that serve the purpose of bridging the gap between problem and solution" (Lewis, 2006, p. 271). For both scientists and engineers, some problems are relatively straightforward; challenging problems, however, are characterized by high levels of uncertainty that require a great deal of creativity on the part of the problem solver. In searching for solutions, engineers and scientists use similar cognitive tools, such as brainstorming, reasoning by analogy, mental models, and visual representations. And both require testing and evaluation of the product—the engineering design or the scientific hypothesis.

One point of divergence between engineering design and scientific inquiry is the role of constraints, which are common to both processes but are fundamental to engineering design. Budget constraints, for example, can limit scientific inquiry and perhaps even keep scientists from answering

a particular question, but they do not affect the answer itself. For engineers, however, budget constraints can determine whether a particular design solution is workable. Another divergence is trade-offs. As Lewis notes (2006), trade-offs are a basic aspect of design but have essentially no part in scientific inquiry.

A related difference is the scientist's emphasis on finding general rules that describe as many phenomena as possible, whereas the engineer's focus is on finding solutions that satisfy particular circumstances. Scientific inquiry begins with a particular, detailed phenomenon and moves toward generalization, while engineering design applies general rules and approaches to zero in on a particular solution. In addition, judgments about the suitability of a design are inevitably shaped by individual and social values; thus the optimal design for one person may not be optimal for another. This is quite different from the scientific method; in the ideal scientific situation, answers are independent of values.

Another way to compare design with the scientific method is to consider the characteristics of the two problem-solving approaches (Box 2-2). *Science*

BOX 2-2
Characteristics of Scientific Inquiry and Engineering Design

Scientific Inquiry:

Demands evidence
Is a blend of logic and imagination
Explains and predicts
Tries to identify and avoid bias
Is not authoritarian

Engineering (or Technological) Design:

Is purposeful
Is based on certain requirements
Is systematic
Is iterative
Is creative
Allows many possible solutions

SOURCES: AAAS, 1989; ITEA, 2000.

for All Americans, published by the American Association for the Advancement of Science, identifies five characteristics of scientific inquiry that distinguish it from other modes of inquiry: science demands evidence; science is a blend of logic and imagination; science explains and predicts; scientists try to identify and avoid bias; and science is not authoritarian (AAAS, 1989). At first glance, these rather general statements seem to apply, at least partly, to engineering design. Certainly engineers also demand evidence, for instance, and they use a blend of logic and evidence in their design work. Conversely, there is little doubt that science can be a very creative endeavor, is systematic, and is purposeful. This overlap reflects the many similarities in the ways scientists and engineers go about their work.

Nevertheless, there are also important differences between the scientific method and engineering design. The distinguishing features of engineering design include taking into account specifications and constraints; dependence on iteration; and the embrace of multiple possible solutions. The differences in the two lists reflect the basic differences between science and engineering—scientists investigate and engineers create.

For example, although "purposeful" might describe a characteristic of the scientific method, it would certainly not appear near the top of the list. For engineering design, however, purposefulness is a fundamental characteristic—the first question that must be answered about any design is, "what is its purpose?" For scientists, however, the focus is on the particular questions they are investigating. Scientists may have an underlying purpose for investigating particular questions—for example, a geneticist studying the BCRA gene does so for the purpose of understanding breast cancer—but the day-to-day work of the scientist is driven by the question, not the purpose.

Similarly, specifications and constraints are not essential to answering scientific questions. Not every scientific question has a single "correct" solution, but there is no expectation in the scientific method that the process will inevitably produce multiple answers. These, however, are fundamental characteristics of design that set it apart from the scientific method.

IMPORTANT CONCEPTS IN ENGINEERING

In addition to specifications and constraints, a number of other concepts are key to understanding what engineers do and how they do it. The list may vary depending on who compiles it, but certain concepts will appear on most lists (e.g., AAAS, 1993; Burghardt, 2007; Childress and Rhodes, 2006; Childress and Sanders, 2007; ITEA, 2000; Sneider, 2006).

One crucial idea that appears regularly on the engineering list, but also on the science list and lists for many other areas of study, is the concept of *systems.* In very general terms a system is a collection of interacting pieces. The collection of all trains, planes, and automobiles, along with railways, airports, roads, and everything else involved in getting people and things from one place to another makes up one type of system—the country's transportation system. The various components of an iPod constitute another kind of system. The machines and their operators in an automobile plant make up another kind of system.

In most cases a system is more than the sum of its parts, and understanding a system involves not only understanding the individual parts but also understanding how the parts interact. Most of the "things" engineers design are systems of one kind or another, and in many cases those things function as part of a larger system. Thus engineers must have a good grasp of how systems work and the factors that influence the performance of the system (AAAS, 1993).

Engineers use *modeling* as a way to understand what may happen when an actual artifact or process is used. In the case of a wooden plank used as a footbridge across a stream, for instance, an engineer might be asked to predict the weight of the heaviest person who could cross the plank without breaking it. The engineer creates a *representational model* of the plank, which may consist of drawings or physical, three-dimensional renditions. The model incorporates assumptions about the size and physical properties of the plank and about how it is secured on the banks of the stream.

Using the representational model, the engineer creates a free-body diagram, which shows the various forces that act on the plank, and from the free-body diagram develops a *mathematical model* based on laws of mechanics. By creating the representational models of potential solutions and then mathematically characterizing them, engineers can predict the behavior of technologies before they are built, and the predictions can be tested experimentally. The accuracy of the representational and mathematical models—often calculated with the assistance of computer programs and/or computer simulations—determines the validity of the predictions. This process of *predictive analysis* is another central feature of engineering design.

Very sophisticated software programs have been developed for predicting the performance of integrated circuit chips, for example. Without these programs, it would be essentially impossible to design the highly sophisticated chips that are manufactured today (EDAC, 2008). Because of the importance of mathematical modeling and predictive analysis to engineer-

ing design, mathematics is essential to engineering, and engineers must be comfortable using mathematical tools.

As mentioned above, one step in design is understanding the requirements, or *specifications* and *constraint*s, of the design. The specifications are key features and elements of the product and what it is supposed to do. Constraints are limitations on the design—physical, financial, social, political, environmental factors, and so on. It is almost never possible to meet all of the specifications and accommodate all of the constraints simultaneously. Determining the best solution to a technical problem requires balancing competing or conflicting factors; this process is called *optimization*. Often different alternatives are better in different ways. One material may be stronger, for instance, but a second material may cost less. Choosing the best solution normally requires *trade-offs*, that is, deciding not to maximize one desirable thing in order to maximize another. Deciding which criteria are the most important is essential to determining the best solution to a problem. The idea is to decide upon a design that comes closest to meeting the specifications, that fits within the constraints, and that has the least number of negative characteristics (AAAS, 1993).

THE RELATIONSHIP OF ENGINEERING TO SCIENCE AND MATHEMATICS

Engineering is intimately related to science and mathematics. Engineers use both science and mathematics in their work, and scientists and mathematicians use the products of engineering in their work. In every field of engineering, an understanding of the relevant science is a prerequisite to doing the job. Chemical engineers must understand chemistry, bioengineers must understand molecular biology, petroleum engineers must understand geology, electronics engineers must understand how electrons behave in various materials, nuclear engineers must understand how the nuclei of atoms behave, and so on. Indeed, science is so fundamental to what engineers do that, in a very real sense, engineering can be thought of as putting science to work.

Mathematics is as fundamental to engineering as science. Engineers use mathematics both to describe data (e.g., graphs showing the strength or other properties of a material under varying conditions) and to analyze them (e.g., the flow rate of fluids through the pipes of a chemical plant). As noted above, engineers use science and mathematics most obviously in building and analyzing models.

Conversely, engineering is essential to science and mathematics. Scientists depend upon the products of engineers—everything from space telescopes to gene sequencers—to perform various manipulations and measurements in exploring the natural world. And although many mathematicians still require little more than chalk and a chalkboard for their studies, a growing number of them now take advantage of increasingly powerful computers—a gift from engineers—to perform mathematical explorations. Thus the relationship between engineering and science and mathematics is a two-way street.

ENGINEERING IN THE TWENTY-FIRST CENTURY

A description of engineering would be incomplete without addressing the challenges the field faces in the coming decades. Of course, looking into the future is always a tricky proposition, but several trends in engineering provide a basis for extrapolating and predicting some things about the future of engineers and engineering.

An Increasingly Diverse Workforce

As shown in Table 2-1, the engineering workforce in the United States today includes relatively few women and minorities compared to the percentages of these groups in the general population and the overall workforce. These numbers indicate that the potential contributions of women and minorities to the engineering workforce are not being realized. Addressing this underrepresentation will be critical to the future of engineering in light of the changing demographics in the United States.

Projections based on current trends indicate that by 2050 minorities will make up almost half of the U.S. population and a corresponding percentage of the U.S. workforce (U.S. Census Bureau, 2002). Thus even if minorities are still underrepresented in the engineering workforce, they will likely account for a much larger percentage of the workforce in coming years. The hope is, of course, that the engineering workforce of the future will be far more diverse and representative than it is today.

Adaptation to a Changing World

The kinds of jobs engineers are being asked to do and the skills they are expected to have are changing (Duderstadt, 2008). A major factor driving

changes in the demands on U.S. engineers is increasing global competition. U.S. engineers increasingly find themselves competing for work with engineers from other countries, who are often paid much less—in some countries as much as 80 percent less. To succeed in this environment, U.S. engineers will need not only the analytic skills—high-level design, systems thinking, and creative innovation—that are taught in engineering courses, but also a variety of skills that are often overlooked in engineering education. These include communications and leadership skills, the flexibility to adapt to changing conditions, the ability to work in multicultural environments, an understanding of the business side of engineering, and a commitment to lifelong learning (NAE, 2004).

Implications for K–12 Engineering Education

As noted in Chapter 1 and discussed at greater length later in the report, one of the purposes of at least some K–12 engineering education programs is to encourage more young people to consider engineering as a career pathway. It is unrealistic to expect that the challenges facing U.S. innovation can be addressed solely by boosting the number and diversity of K–12 students interested in technical and scientific fields. But broadening the appeal of engineering and related careers to American pre-college students will almost certainly be part of the solution.

REFERENCES

AAAS (American Association for the Advancement of Science). 1989. Science for All Americans. New York: Oxford University Press.

AAAS. 1993. Benchmarks for Science Literacy. New York: Oxford University Press.

Aicher, P.J. 1995. Guide to the Aqueducts of Ancient Rome. Wauconda, Ill.: Bolchazy-Carducci Publishers.

ASEE (American Society for Engineering Education). 2007a. Profiles of Engineering and Engineering Technology Colleges. ASEE 2006 Edition. Washington, D.C.: ASEE.

ASEE. 2007b. Engineering and Technology Degrees. Engineering Workforce Commission of the American Association of Engineering Societies, Inc. Washington, D.C.: ASEE.

BLS (Bureau of Labor Statistics). 2008a. Occupational Outlook Handbook, 2008–09 Edition, Engineers. Available online at *http://www.bls.gov/oco/ocos027.htm* (accessed November 24, 2008).

BLS. 2008b. Occupational Outlook Handbook, 2008–09 Edition, Engineering Technicians. Available online at *http://www.bls.gov/oco/ocos112.htm* (accessed December 3, 2008).

Burghardt, D. 2007. What is engineering?—Perspectives on K–12 engineering. Paper prepared for the NAE/NRC Committee on K–12 Engineering Education. July 23, 2007. Unpublished.

Calhoun, D.H. 1960. The American Civil Engineer: Origins and Conflict. Cambridge: The Technology Press.

Childress, V., and C. Rhodes. 2006. Engineering Student Outcomes for Grades 9–12. National Center for Engineering and Technology Education, Utah State University, Logan, Utah. Available online at *http://ncete.org/flash/Outcomes.pdf* (accessed September 2, 2008).

Childress, V., and M. Sanders. 2007. Core Engineering Concepts Foundational for the Study of Technology in Grades 6-12. Available online at *http://www.conferences.ilstu.edu/NSA/papers/ChildressSanders.pdf* (accessed September 2, 2008).

CTTE (Council on Technology Teacher Education). 2008. Engineering and Technology Education, 57th Yearbook, R.L. Custer and T.L. Erekson, eds. Woodland Hills, Calif.: Glencoe/McGraw-Hill.

DOEd (United States Department of Education). 2006a. Digest of Education Statistics, 2005 (NCES 2006-030), Table 205. National Center for Education Statistics. Available online at *http://nces.ed.gov/fastfacts/display.asp?id=98* (accessed December 22, 2008).

DOEd. 2006b. Digest of Education Statistics, 2005 (NCES 2006-030), Table 170. National Center for Education Statistics. Available online at *http://nces.ed.gov/programs/digest/d05/tables/dt05_170.asp* (accessed December 22, 2008).

Duderstadt, J. J. 2008. Engineering for a Changing World: A Roadmap to the Future of Engineering Practice, Research, and Education. The Millennium Project. Available online at *http://milproj.ummu.umich.edu/publications/EngFlex%20report/download/EngFlex%20Report.pdf* (accessed December 19, 2008).

EDAC (Electronic Design Automation Consortium). 2008. EDA Industry. What is EDA? Available online at *http://www.edac.org/industry_what_is_eda.jsp* (December 23, 2008.)

Evans, H.B. 1994. Water Distribution in Ancient Rome: The Evidence of Frontinus. Ann Arbor, Mich.: University of Michigan Press.

Flexner, S.B. 1987. The Random House Dictionary of the English Language, Second Edition—Unabridged. New York: Random House.

Grinter, L.E. 1984. Engineering and engineering technology education. Journal of Engineering Technology 1(1): 6–8.

Herschbach, D.R. 2009. Technology Education—Foundations and Perspectives. Homewood, Ill.: American Technical Publishers, Inc.

ITEA (International Technology Education Association). 2000. Standards for Technological Literacy: Content for the Study of Technology. Reston, Va.: ITEA.

Langins, J. 2004. Conserving the Enlightenment: French Military Engineering from Vauban to the Revolution. Cambridge, Mass.: MIT Press.

Lewis, T. 2004. A Turn to Engineering: The continuing struggle of technology education for legitimization as a school subject. Journal of Technology Education 16(1): 21-39. Available online at: *http://scholar.lib.vt.edu/ejournals/JTE/v16n1/pdf/lewis.pdf* (accessed May 29, 2009).

Lewis, T. 2006. Design and inquiry: Bases for an accommodation between science and technology education in the curriculum? Journal of Research in Science Teaching 43(3): 255–281.

Lucena, J.C. 2005. Defending the Nation: U.S. Policymaking to Create Scientists and Engineers from Sputnik to the 'War against Terrorism.' New York: University Press of America.

McAlister, B. 2005. Are Technology Education Teachers Prepared to Teach Engineering Design and Analytical Methods? Paper presented at the International Technology Education Association Conference, Session IV: Technology Education and Engineering, Kansas City, Missouri, April 4, 2005.

Miller, J. 2008. Overview of Engineering and Technical Education and Work in the United States. Paper prepared for the NAE/NRC Committee on K–12 Engineering Education. May 13, 2008. Unpublished.

NAE (National Academy of Engineering). 2004. The Engineer of 2020—Visions of Engineering in the New Century. Washington, D.C.: The National Academies Press.

NAE. 2008. Changing the Conversation: Messages for Improving Public Understanding of Engineering. Washington, D.C.: The National Academies Press.

NSF (National Science Foundation). 2005a. Science and Engineering Degrees: 1966–2004. Table 47: Engineering degrees awarded, by degree level and sex of recipient, 1966–2004. Available online at *http://www.nsf.gov/statistics/nsf07307/pdf/tab47.pdf* (accessed January 4, 2008).

NSF. 2005b. Women, Minorities, and Persons with Disabilities in Science and Engineering. Table C-7: Racial/ethnic distribution of S&E bachelor's degrees awarded to U.S. citizens and permanent residents, by field: 1995–2005. Available online at *http://www.nsf.gov/statistics/wmpd/pdf/tabc-7.pdf* (accessed January 4, 2008).

NSF. 2006a. Science and Engineering Indicators 2006. Appendix Table 2-26: Earned bachelor's degrees, by field and sex: Selected years, 1983–2002. Available online at *http://nsf.gov/statistics/seind06/append/c2/at02-26.xls* (accessed September 18, 2007).

NSF. 2006b. Science and Engineering Indicators 2006. Figure 3-26: Women as proportion of employment in S&E occupations, by broad occupation: 1983 and 2003. Available online at *http://www.nsf.gov/statistics/seind06/c3/c3s1.htm#c3s1l11* (accessed January 4, 2008).

Reynolds, T.S. 1991. The Engineer in 19th-Century America. Pp. 7,8,13 in The Engineer in America: A Historical Anthology from Technology and Culture, edited by T.S. Reynolds. Chicago, Ill.: Chicago University Press.

Sanders, M. 2008. The Nature of Technology Education in the United States. Paper presented at the Annual Conference of the American Society of Engineering Education, Pittsburgh, Pa., June 25, 2008.

Sneider, C. 2006. Draft Learning Progression for Engineering Design. Boston Museum of Science, November 12, 2006. Unpublished.

U.S. Census Bureau. 2002. Current Population Reports: Population Projections of the United States by Age, Sex, Race, and Hispanic Origin: 1995 to 2050. Table J. Available online at *http://www.census.gov/prod/1/pop/p25-1130.pdf* (accessed September 18, 2007).

U.S. Census Bureau. 2005. Race and Hispanic Origin in 2005. Population Profile of the United States: Dynamic Version. Available online at *http://www.census.gov/population/pop-profile/dynamic/RACEHO.pdf* (accessed October 26, 2007).

Wadhwa, V., G. Gereffi, B. Rissing, and R. Ong. 2007. Where the engineers are. Issues in Science and Technology (Spring): 73–84.

Wulf, W.A. 1998. The image of engineering. Issues in Science and Technology. Winter. Available online at *www.issues.org/15.2/wulf.htm* (accessed May 16, 2009).

able online at *http://www.census.gov/prod/1/pop/p25-1130.pdf* (accessed September 18, 2007).

U.S. Census Bureau. 2005. Race and Hispanic Origin in 2005. Population Profile of the United States: Dynamic Version. Available online at *http://www.census.gov/population/pop-profile/dynamic/RACEHO.pdf* (accessed October 26, 2007).

Wadhwa, V., G. Gereffi, B. Rissing, and R. Ong. 2007. Where the engineers are. Issues in Science and Technology (Spring): 73–84.

Wulf, W.A. 1998. The image of engineering. Issues in Science and Technology. Winter. Available online at *www.issues.org/15.2/wulf.htm* (accessed May 16, 2009).